109205



# Declaration under 37 C.F.R. §1.132

I, Daijiro Inoue, a citizen of Japan, hereby declare the following:

1. I graduated in Kyoto Institute of Technology. My research involved analysis of amorphous materials.

2. Since 1985, I have been employed by Sanyo Electric Co., LTD, and affiliated with R&D Headquarters. I am and have been engaged in the research and development of compound semiconductor electronic and optical devices.

3. I am a co-inventor of the invention of United States Patent Application No. 09/746,065.

4. I have read and am familiar with the above-identified patent application as well as the Final Office Action dated February 11, 2003, and the cited references therein.

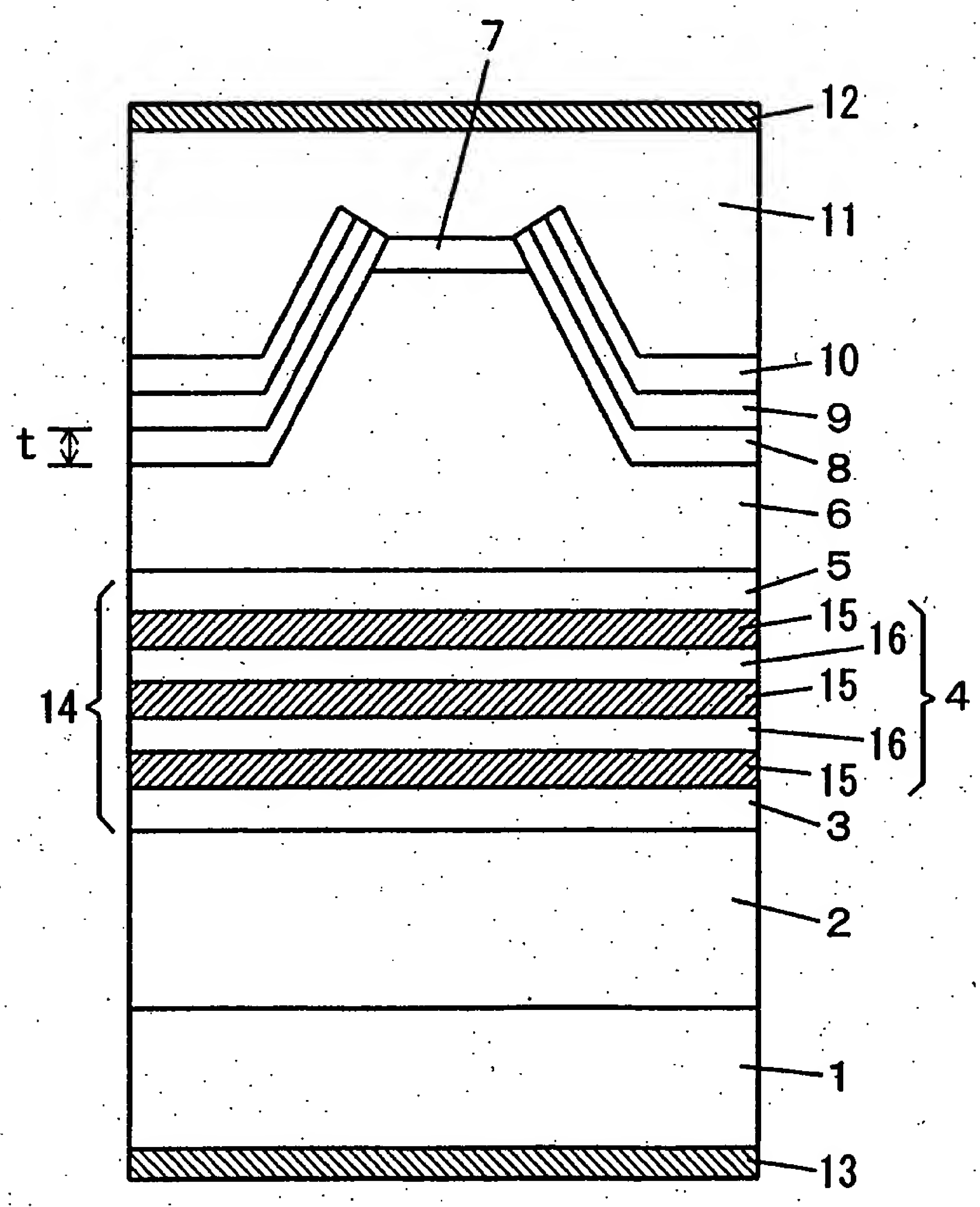


5. I declare that I conducted the following three experimental investigations, which show unexpected results associated with the thickness of a depletion enhancement layer in a semiconductor device of the present invention:

**Background of the Experiments**

FIG. 1 is a typical sectional view of a semiconductor laser device according to an embodiment of the present invention. In the semiconductor laser device shown in FIG. 1, a cladding layer 2 of n-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ having a thickness of 1500 nm and an emission layer 14 described later are successively formed on an n-GaAs substrate 1. A cladding layer 2 of p-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ having a thickness of 1500 nm and a contact layer of p-$Ga_{0.5}In_{0.5}P$ having a thickness of 200 nm are successively formed on the emission layer 14. The p- type cladding layer 6 and the p-type contact layer 7 are etched to define a ridge portion.

FIG. 1



The carrier concentration of the n-GaAs substrate 1 is $1*10^{18}$ $cm^{-3}$, the carrier concentration of the n-type cladding layer 2 is $3*10^{17}$ $cm^{-3}$, and the carrier concentration of the p-type contact layer 7 is $2*10^{18}$ $cm^{-3}$, respectively.

Further, a depletion enhancement layer 8 of a thickness t having a striped opening on the upper surface of the ridge portion is formed on the p-type cladding layer 6. A low carrier concentration layer 9 of GaAs of 1000 nm in thickness having a striped opening on the upper surface of the ridge portion is formed on the depletion enhancement layer 8. An n-type current blocking layer 10 of n-GaAs of 500 nm in thickness having a striped opening on the upper surface of the ridge portion is formed on the low carrier concentration layer 9. The carrier concentration of the n-type current blocking layer 10 is $8*10^{17}$ $cm^{-3}$. The carrier concentration of the low carrier concentration layer 9 is lower than that of the n-type current blocking layer 10.

A contact layer 11 of p-GaAs having a thickness of 3000 nm is formed on the p-type contact layer 7 located in the striped opening of the n-type current blocking layer 10 and on the n-type current blocking layer 10. The carrier concentration of the p-type contact layer is $3*10^{19}$ $cm^{-3}$. A p-electrode 12 having a thickness of 300 nm is formed on the p-type contact layer 11. An n electrode 13 having a thickness of 300 nm is formed on the back side of the n-GaAs substrate 1.

The emission layer 14 includes a guide layer 3 of $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ having a thickness of 30 nm formed on the n- type cladding layer 2, a quantum well active layer 4 formed on the guide layer 3 and a guide layer 5 of $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ having a thickness of 30 nm formed on the quantum well active layer 4.

The quantum well active layer 4 has a superlattice structure formed by alternately stacking a plurality of quantum well layers 15 of $Ga_{0.5}In_{0.5}P$ each having a thickness of 5 nm and a plurality of barrier layers 16 of $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ each having a thickness of 5 nm. For example, the number of the barrier layers 16 is 2, and the number of the quantum well layers 15 is 3.

Table 1 shows the aforementioned structure.

Table 1

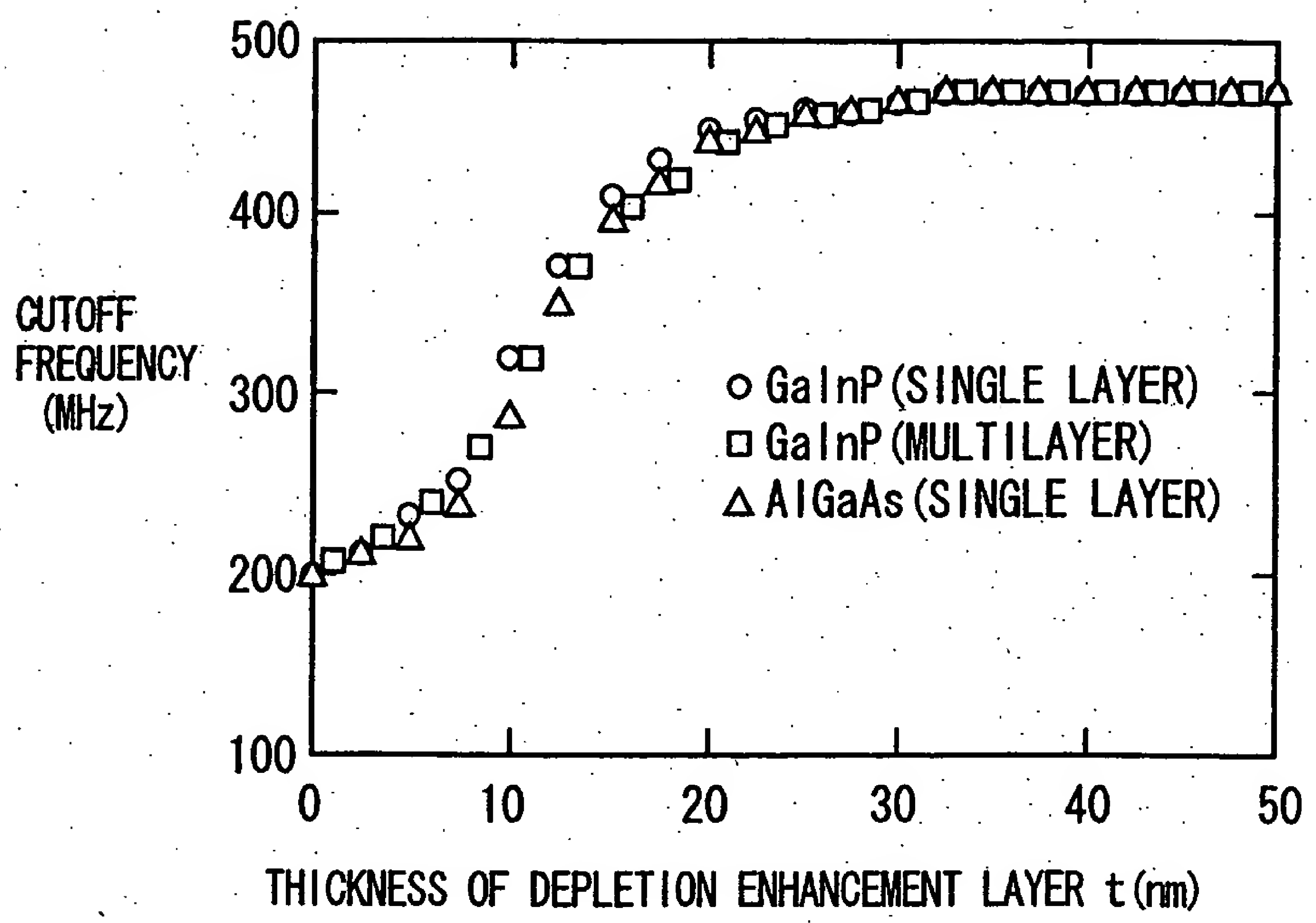
| Name of Layer | | Composition and Name of Layer | Thickness (nm) | Carrier Concentration ($cm^{-3}$) | Numeral |
|---|---|---|---|---|---|
| | | n-GaAs Substrate | | $1\times10^{18}$ | 1 |
| | | Cladding Layer of n-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ | 1500 | $3\times10^{17}$ | 2 |
| | | Guide Layer of $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ | 30 | | 3 |
| Emission Layer | Quantum Well Active Layer | Quantum Well Layer of $Ga_{0.5}In_{0.5}P$ | 5 | | 15 |
| | | Barrier Layer of $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ | 5 | | 16 |
| | | Guide Layer of $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ | 30 | | 5 |
| | | Cladding Layer of p-$(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ | 1500 | $3\times10^{17}$ | 6 |
| | | Contact Layer of p-$Ga_{0.5}In_{0.5}P$ | 200 | $2\times10^{18}$ | 7 |
| | | Depletion Enhancement Layer of $Ga_{0.5}In_{0.5}P$ | t | | 8 |
| | | Low Carrier Concentration Layer of GaAs | 1000 | | 9 |
| | | Current Blocking Layer of n-GaAs | 500 | $8\times10^{17}$ | 10 |
| | | Contact Layer of p-GaAs | 3000 | $3\times10^{19}$ | 11 |
| | | p-Electrode | 300 | | 12 |
| | | n-Electrode | 300 | | 13 |

The cutoff frequency is such a frequency that the amplitude of a laser beam superposed with a sine wave output from the object semiconductor laser device is reduced by 3 dB as compared with the case of superposing a low frequency (the superposed frequency is not more than 10 MHz in this example).

**First Experiment**

The present inventors investigated the effects on cutoff frequency of varying the thickness t of the depletion enhancement layer 8 of the above structure. Thicknesses of less than 10 nm to 50 nm were studied. FIG. 6 shows the results of measurement of a cutoff frequency of the semiconductor laser device shown in Table 1 with variation of the thickness t of the depletion enhancement layer 8.

FIG. 6




Referring to FIG. 6, ○ denotes a case of employing a depletion enhancement layer 8 of $Ga_{0.5}In_{0.5}P$ having a single-layer structure, □ denotes a case of employing a depletion enhancement layer 8 of a superlattice structure alternately having $(Al_{0.7}Ga_{0.3})_{0.5}In_{0.5}P$ barrier layers and $Ga_{0.5}In_{0.5}P$ well layers (the thickness t is the sum of the thicknesses of the well layers), and Δ denotes a case of employing a depletion enhancement layer 8 of $Al_{0.45}Ga_{0.55}As$ having a single-layer structure respectively.

FIG. 6 clearly shows that the cutoff frequency, which was 200 MHz when the semiconductor laser device was formed with no depletion enhancement layer 8, is improved when the thickness t of the depletion enhancement layer 8 is increased, and remarkably improved when the thickness t of the depletion enhancement layer 8 exceeds 10 nm, and substantially saturated when the thickness t is about 20 nm. Therefore, the thickness t of the depletion enhancement layer 8 is preferably at least 10 nm, and more preferably at least 20 nm saturating improvement of the cutoff frequency. When the thickness t of the depletion enhancement layer 8 is at least 15 nm, the intermediate level between 10 nm and 20 nm, the high-frequency characteristic is sufficiently improved.

## Second Experiment

The structure of a semiconductor laser device evaluated in a second experiment is similar to that shown in FIG. 1, while the materials, thicknesses and carrier concentrations of respective layers are different from those in the first experiment. Table 2 shows the materials, thicknesses and carrier concentrations of the respective layers forming the semiconductor laser device according to this embodiment.

Table 2

| Name of Layer | | Composition and Name of Layer | Thickness (nm) | Carrier Concentration ($cm^{-3}$) | Numeral |
|---|---|---|---|---|---|
| | | n-GaAs Substrate | | $1\times10^{18}$ | 1 |
| | | Cladding Layer of n-$Al_{0.45}Ga_{0.55}As$ | 1500 | $3\times10^{17}$ | 2 |
| Emission Layer | | Guide Layer of $Al_{0.35}Ga_{0.65}As$ | 30 | | 3 |
| | Quantum Well Active Layer | Quantum Well Layer of $Al_{0.1}Ga_{0.9}As$ | 5 | | 15 |
| | | Barrier Layer of $Al_{0.35}Ga_{0.65}As$ | 5 | | 16 |
| | | Guide Layer of $Al_{0.35}Ga_{0.65}As$ | 30 | | 5 |
| | | Cladding Layer of p-$Al_{0.45}Ga_{0.55}As$ | 1500 | $1\times10^{18}$ | 6 |
| | | Contact Layer of p-GaAs | 200 | $4\times10^{18}$ | 7 |
| | | Depletion Enhancement Layer of $Al_{0.25}Ga_{0.75}As$ | t | | 8 |
| | | Low Carrier Concentration Layer of GaAs | 1000 | | 9 |
| | | Current Blocking Layer of n-GaAs | 500 | $5\times10^{17}$ | 10 |
| | | Contact Layer of p-GaAs | 3000 | $3\times10^{19}$ | 11 |
| | | p-Electrode | 300 | | 12 |
| | | n-Electrode | 300 | | 13 |

The present inventors investigated the effects on cutoff frequency of varying the thickness t of the depletion enhancement layer 8 of the above structure. Thicknesses of less than 10 nm to 50 nm were studied. FIG. 8 illustrates results of measurement of a cutoff frequency of the semiconductor laser device shown in Table 2 with variation of the thickness t of a depletion enhancement layer 8. Referring to FIG. 8, ○ denotes a case of employing a depletion enhancement layer 8 of $Al_{0.25}Ga_{0.75}As$ having a single-layer structure, and □ denotes a case of employing a depletion enhancement layer 8 of a superlattice structure alternately having $Al_{0.45}Ga_{0.55}As$ barrier layers and $Al_{0.25}Ga_{0.75}As$ well layers (the thickness t is the sum of the thicknesses of the well layers).

FIG. 8

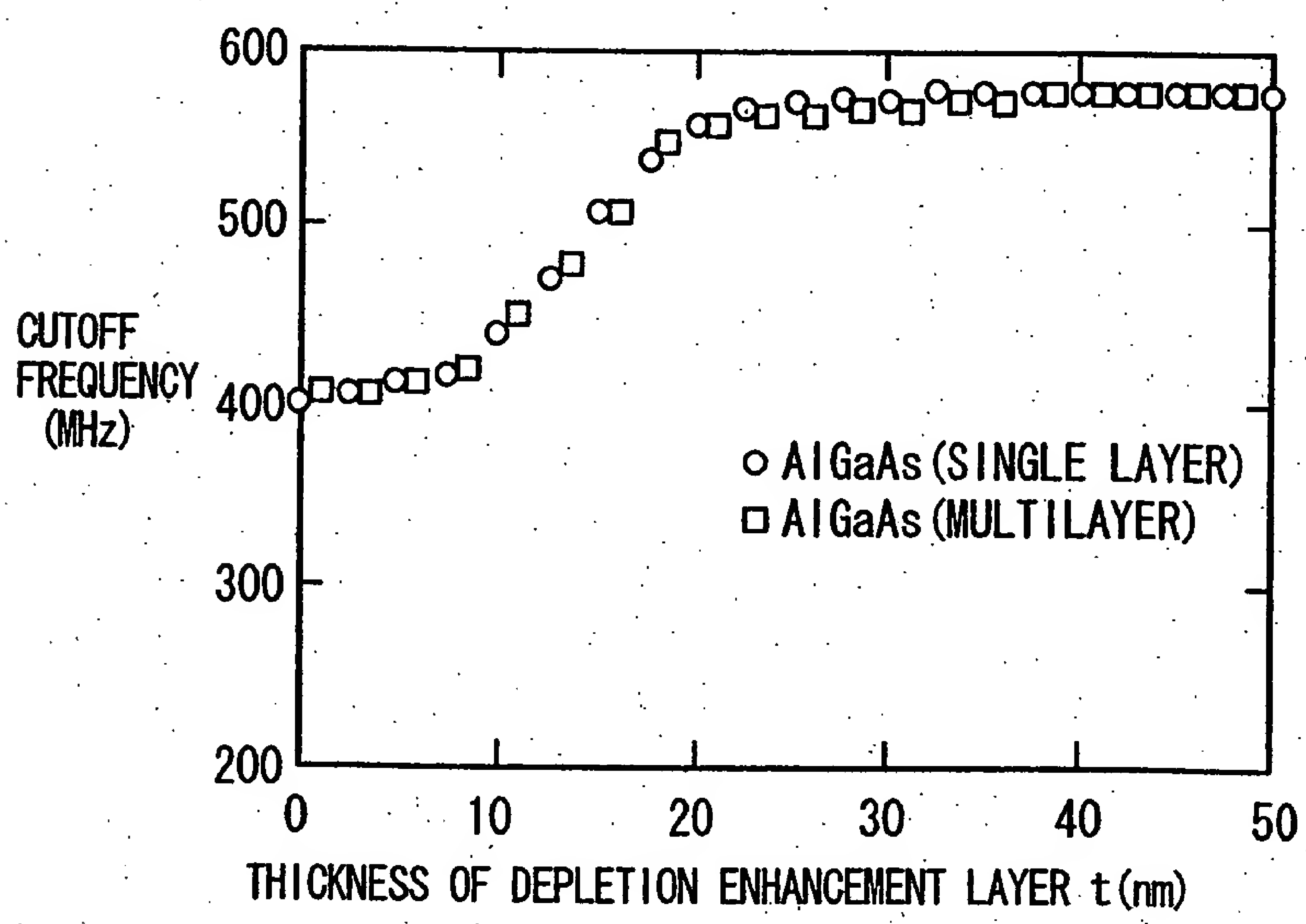



FIG. 8 clearly shows that the cutoff frequency, which was 400 MHz when the semiconductor laser device is formed with no depletion enhancement layer 8, is improved when the thickness t of the depletion enhancement layer 8 is increased, remarkably improved when the thickness t of the depletion enhancement layer 8 exceeds 10 nm, and substantially saturated when the thickness

t is about 20 nm. Therefore, the thickness t of the depletion enhancement layer 8 is preferably at least 10 nm, and more preferably at least 20 nm saturating improvement of the cutoff frequency. When the thickness t of the depletion enhancement layer 8 is at least 15 nm, the intermediate level between 10 nm and 20 nm, the high-frequency characteristic is sufficiently improved.

**Third Experiment**

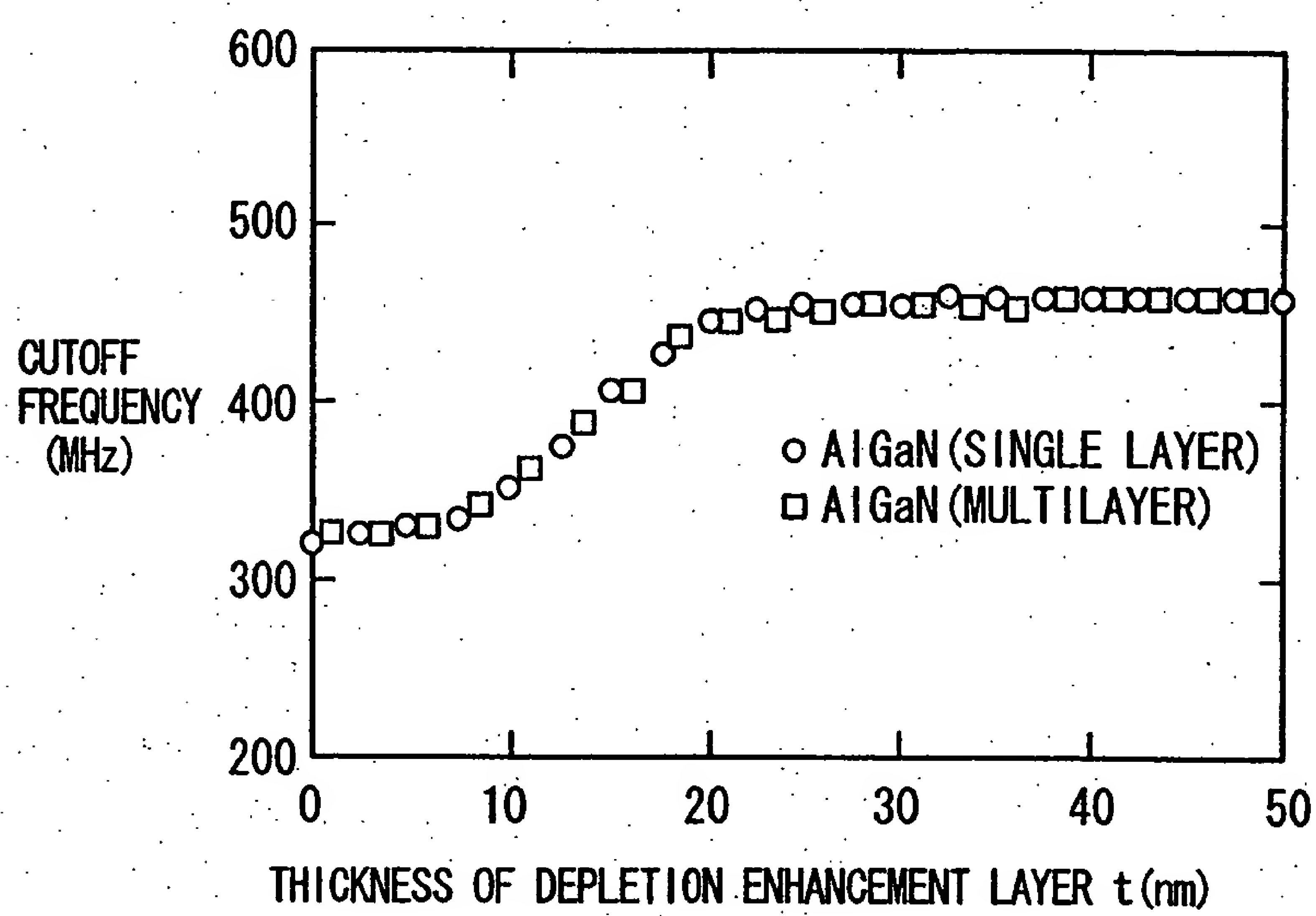
The structure of the semiconductor laser device evaluated in a third experiment is similar to that shown in FIG. 1, while the materials, thicknesses and carrier concentrations of respective layers are different from those in the first embodiment. Table 3 shows the materials, thicknesses and carrier concentrations of the respective layers forming the semiconductor laser device according to this embodiment.

Table 3

| Name of Layer | | Composition and Name of Layer | Thick-ness (nm) | Carrier Concent-ration ($cm^{-3}$) | Nu-mer-al |
|---|---|---|---|---|---|
| | | n-GaN Substrate | | $1\times10^{18}$ | 1 |
| | | Cladding Layer of n-$Al_{0.15}Ga_{0.85}N$ | 1000 | $3\times10^{17}$ | 2 |
| Emission Layer | | Guide Layer of GaN | 30 | | 3 |
| | Quantum Well Active Layer | Quantum Well Layer of $In_{0.15}Ga_{0.85}N$ | 5 | | 15 |
| | | Barrier Layer of $In_{0.05}Ga_{0.95}N$ | 5 | | 16 |
| | | Guide Layer of GaN | 30 | | 5 |
| | | Cladding Layer of p-$Al_{0.15}Ga_{0.85}N$ | 1000 | $2\times10^{17}$ | 6 |
| | | Contact Layer of p-GaN | 200 | $3\times10^{17}$ | 7 |
| | | Depletion Enhancement Layer of $Al_{0.07}Ga_{0.93}N$ | t | | 8 |
| | | Low Carrier Concentration Layer of GaN | 800 | | 9 |
| | | Current Blocking Layer of n-GaN | 200 | $5\times10^{17}$ | 10 |
| | | Contact Layer of p-GaN | 3000 | $8\times10^{17}$ | 11 |
| | | p-Electrode | 300 | | 12 |
| | | n-Electrode | 300 | | 13 |

FIG. 9 illustrates results of measurement of a cutoff frequency of the semiconductor laser device shown in Table 3 with variation of the thickness t of a depletion enhancement layer 8. Referring to FIG. 9, ○ denotes a case of employing a depletion enhancement layer 8 of $Al_{0.07}Ga_{0.93}N$ having a single-layer structure, and □ denotes a case of employing a depletion enhancement layer 8 of a superlattice structure alternately having $Al_{0.15}Ga_{0.85}N$ barrier layers and $Al_{0.07}Ga_{0.93}N$ well layers (the thickness t is the sum of the thicknesses of the well layers).

FIG. 9




The present inventors investigated the effects on cutoff frequency of varying the thickness t of the depletion enhancement layer 8 of the above structure. Thicknesses of less than 10 nm to 50 nm were studied. FIG. 9 clearly shows that the cutoff frequency, which was 320 MHz when the semiconductor laser device is formed with no depletion enhancement layer 8, is gradually improved when the thickness t of the depletion enhancement layer 8 is increased, remarkably improved when the thickness t of the depletion enhancement layer 8 exceeds 10 nm, and substantially saturated when the thickness t is about 20 nm. Therefore, the thickness t of the

depletion enhancement layer 8 is preferably at least 10 nm, and more preferably at least 20 nm saturating improvement of the cutoff frequency. When the thickness t of the depletion enhancement layer 8 is at least 15 nm, the intermediate level between 10 nm and 20 nm, the high-frequency characteristic is sufficiently improved.

**Summary**

The above experiments clearly show the unexpected result associated with the thickness of the depletion enhancement layer of a semiconductor device of the present invention being in the range of 10-20 nm.

Signed,

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Daijiro Inoue        Nov. 6, 2003

Daijiro Inoue        Date